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ANALYTICAL CONSIDERATIONS REGARDING A CONTROL-SURFACE

BALANCE ARRANGEMENT FOR SUBSONIC

AND SUPERSONIC FLIGHT

By

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ANALYTICAL CONSIDERATIONS REGARDING A CONTROL-SURFACE
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SUMMARY

The possibility of utilizing the principle of the sealed internal balance in a device capable of reducing control-surface hinge moments at both subsonic and supersonic speeds has been investigated by means of simple theoretical considerations. The analysis indicates that satisfactory balance performance may possibly be obtained at subsonic flight speeds below the speed at which local sonic velocities occur and in fully developed supersonic flow, provided that the balance chamber is vented to the air stream at a location approximately midway between the control-surface hinge line and the wing trailing edge. Such a balance also appears to have certain points in its favor for operation at transonic speeds.

INTRODUCTION

Control-surface balances normally provided on aircraft that operate at speeds well below sonic speed generally are designed to take advantage of the particular characteristics of subsonic incompressible flow. Such balances usually become unsatisfactory whenever large deviations from low-speed flow characteristics exist; consequently, on many recent high-speed airplane designs, aerodynamic balances have been abandoned in favor of mechanical booster systems.

A control-surface balance capable of satisfactory performance at low subsonic, transonic, and supersonic speeds might be used advantageously either as the only means of reducing the control forces or as a means of supplementing the effect of a low-power booster system. In the latter application, failure of the booster might not prevent the pilot from applying the amount of control necessary to maintain flight.

Satisfactory balance at any flight speed could be obtained if it were possible to cause the balancing power to be directly proportional to the

moment of the load carried by the control surface. A means of approximating this condition seems feasible through an application of the principle of the sealed internal balance. In the present paper a simplified analysis is made to indicate the design considerations and the possible advantages of such a balance.

SYMBOLS

C_h	flap hinge-moment coefficient $\left(\frac{H}{qb_f c_f^2} \right)$
ΔC_h	hinge-moment-coefficient increment contributed by balance
P_R	resultant pressure coefficient $\left(\frac{P_{\text{Lower}} - P_{\text{Upper}}}{q} \right)$
q	dynamic pressure
p	local surface pressure
H	flap hinge moment
c	wing chord
c_f	flap chord
c_b	balance chord
b	wing span
b_f	flap span
b_b	balance span
α	angle of attack
δ_f	flap deflection
δ_b	balance deflection
t	thickness of flap at hinge line
x	distance rearward from wing leading edge to any arbitrary chordwise station
x_v	distance rearward from wing leading edge to balance-chamber vents

$$C_{h\alpha} = \left(\frac{\partial C_h}{\partial \alpha} \right)_{\delta_f}$$

$$C_{h\delta} = \left(\frac{\partial C_h}{\partial \delta_f} \right)_{\alpha}$$

$$P_{R\alpha} = \left(\frac{\partial P_R}{\partial \alpha} \right)_{\delta_f}$$

$$P_{R\delta} = \left(\frac{\partial P_R}{\partial \delta_f} \right)_{\alpha}$$

Subscripts:

o	plain flap
b	balanced flap
M = 0	limited to Mach numbers approaching zero
max	maximum

Subscripts outside the parentheses of the partial derivatives indicate the factors held constant for evaluation of the derivatives.

BASIC CONSIDERATIONS

The application of a control-surface balance at various flight speeds is considered in the present paper. For convenience, the terms "subsonic," "transonic," and "supersonic" are applied to flight speeds below, within, and above the speed range for which local velocities, both below and above the local speed of sound, occur simultaneously on the airfoil.

The conventional arrangement of a sealed internal balance, as described in reference 1, consists of a balance plate attached rigidly to the nose of a flap and contained within a chamber that is completely sealed except for vents between the flap nose and the balance-chamber cover plates. At speeds well below the speed of sound, deflection of the flap results in an appreciable load over the entire chord of the airfoil - with a peak load at the

hinge line. Under ideal conditions the pressure difference across the balance plate is equal to the pressure difference between the upper and lower surfaces of the airfoil in the vicinity of the vents. Since the vents are located near the pressure peak, balancing pressures of considerable magnitude are obtained at subsonic speeds. In the transonic-speed range, the flap-induced pressures at the vents may decrease considerably, whereas the distribution of load carried by the flap may change in such a manner as to increase the hinge moment resulting from that load. The balance, therefore, might be expected to lose its effectiveness in reducing the flap hinge moments, and the loss is complete when fully developed supersonic flow is attained, since under such conditions the flap induces no load forward of the hinge line.

The principle of the sealed internal balance lends itself to extreme flexibility in design, since it is conceivable that by means of linkages and ducts the balance chamber could be placed at any reasonable location within the airplane structure and the vents could be placed at any suitable location. A possible arrangement that might be expected to operate satisfactorily in subsonic flow and in fully developed supersonic flow is illustrated in figure 1. The principle of its operation can be demonstrated by means of the pressure diagrams on the same figure. The configuration shown has a balance plate attached to the flap nose, but the vents are located some distance to the rear of the flap hinge line, and the pressures are transmitted to the balance chamber by means of ducts within the flap. For fully developed supersonic flow the pressures resulting from flap deflection would approximate the rectangular distribution predicted by the linearized theory of reference 2 and illustrated in figure 1. The pressures transmitted to the balance plate therefore should be almost the same for any vent location to the rear of the hinge line. At subsonic speeds the distribution of pressure over the chord of the flap is more nearly triangular in shape, and therefore the pressures transmitted to the balance plate become smaller as the vents are moved rearward from the flap hinge line. By properly positioning the vents any desired reduction of the flap hinge moments in both subsonic and fully developed supersonic flow probably could be obtained. In the transonic-flow regime, the balance may still operate satisfactorily since the balancing pressures are directly related to the load that causes the hinge moment of the basic flap.

For the balance arrangement illustrated in figure 1 the maximum available deflection of the flap would be rather small for thin wing sections, since the balance plate deflects at the same rate as the flap and would have to be of almost the same chord as the flap in order to balance out a large proportion of the hinge moment. In a more general case, the balance plate might be hinged some distance forward of the flap hinge, or at any other convenient location. A suitable linkage then would be provided to transmit the balancing moment to the flap.

ANALYSIS

Methods of calculating the incremental flap hinge-moment coefficient contributed by a simple attached sealed internal balance, such as that illustrated in figure 1, are given in references 3 and 4. These methods include consideration of the effects of several different arrangements of the flexible nose seal. For many common arrangements, the effect of the seal is small enough to be neglected, and, in such instances, the contribution of the balance can be approximated by

$$\Delta C_h = \frac{1}{2} P_R \left[\left(\frac{c_b}{c_f} \right)^2 - \left(\frac{t/2}{c_f} \right)^2 \right] \frac{b_b}{b_f}$$

provided P_R is the external resultant pressure at the location of the vents. For thin wing sections, or for a balance detached from the flap, the term related to the flap thickness at the hinge line $\left(\frac{t/2}{c_f} \right)^2$ can be

omitted. Now, if the balance plate is geared to the flap through an arbitrary linkage, the hinge-moment-coefficient increment can be expressed as

$$\Delta C_h = \frac{1}{2} P_R \left(\frac{c_b}{c_f} \right)^2 \frac{b_b}{b_f} \frac{\partial \delta_b}{\partial \delta_f}$$

and the total hinge-moment coefficient for the flap with geared balance is

$$C_{h_b} = C_{h_o} + \frac{1}{2} P_R \left(\frac{c_b}{c_f} \right)^2 \frac{b_b}{b_f} \frac{\partial \delta_b}{\partial \delta_f} \quad (1)$$

In fully developed supersonic flow, for which the external resultant pressures are constant over the flap chord, the hinge-moment coefficient of a plain (unbalanced) flap is, according to the linearized theory of reference 2,

$$C_{h_o} = - \frac{1}{2} P_R \quad (2)$$

By means of equations (1) and (2), therefore, the ratio of the hinge-moment coefficient of the balanced flap to the hinge-moment coefficient of the plain flap for idealized supersonic flow is found to be

$$\left(\frac{C_{h_b}}{C_{h_o}} \right)_{\text{supersonic}} = 1 - \left(\frac{c_b}{c_f} \right)^2 \frac{b_b}{b_f} \frac{\partial \delta_b}{\partial \delta_f} \quad (3)$$

This will be referred to as the supersonic hinge-moment ratio, and, as indicated by equation (3), depends only on the geometry of the flap and balance.

Equation (1) applies to either subsonic or supersonic flow, provided appropriate values of the aerodynamic quantities C_{h_o} and P_R are used.

If, for simplification, two-dimensional conditions are assumed, the subsonic resultant pressures and hinge moments might be assumed to vary with Mach number in accordance with the Prandtl-Glauert factor; that is,

$$P_R = \frac{1}{\beta} P_{R_{M=0}}$$

and

$$C_{h_o} = \frac{1}{\beta} C_{h_o_{M=0}}$$

where

$$\beta = \sqrt{1 - M^2}$$

By means of these relations and equations (1) and (3), the subsonic hinge-moment coefficient of a flap with a geared balance can be expressed as

$$\beta C_{h_b} = C_{h_o_{M=0}} + \frac{1}{2} P_{R_{M=0}} \left[1 - \left(\frac{C_{h_b}}{C_{h_o}} \right)_{\text{supersonic}} \right]$$

The subsonic hinge-moment derivatives, with respect to flap deflection and angle of attack, therefore are

$$\beta C_{h_{\delta_b}} = C_{h_{\delta_o_{M=0}}} + \frac{1}{2} P_{R_{\delta_{M=0}}} \left[1 - \left(\frac{C_{h_b}}{C_{h_o}} \right)_{\text{supersonic}} \right] \quad (4)$$

and

$$\beta C_{h\alpha_b} = C_{h\alpha_{M=0}} + \frac{1}{2} P_{R\alpha_{M=0}} \left[1 - \left(\frac{C_{hp}}{C_{ho}} \right)_{\text{supersonic}} \right] \quad (5)$$

In practice it is usually found that boundary-layer effects on hinge moments may approximately cancel the compressibility effects as indicated by the Prandtl-Glauert factor β . Substitution of the value 1.0 for β , therefore, probably would yield results more nearly in accord with experiment. Whether the factor β is dropped or retained is of little importance, however, for the purpose of the present analysis.

In the application of equations (4) and (5) it is presumed that the size and linkage of the balance would be selected to provide a desired reduction of the supersonic hinge moments, as given by the ratio $\left(\frac{C_{hp}}{C_{ho}} \right)_{\text{supersonic}}$.

When this ratio has been selected, only the vent location for satisfactory subsonic operation needs to be determined.

The resultant external pressures and plain-flap hinge-moment parameters for the NACA 0009 airfoil, as given in figures 140 and 142, respectively, of reference 1, have been used as the basis of a simplified analysis to indicate suitable vent locations for satisfactory subsonic performance. The results obtained are considered to be illustrative, since, for a specific design, hinge moments and pressures appropriate to the airfoil in question should be used. Subsonic values of the quantities $\beta C_{h\alpha}$ and $\beta C_{h\delta}$, corresponding to various vent locations, supersonic hinge-moment ratios, and flap-chord ratios were calculated from equations (4) and (5) and the results are presented in figure 2. The calculations indicate that for almost any desired supersonic hinge-moment ratio, subsonic overbalance can be avoided by locating the vents sufficiently far back.

The results given in figure 2 have been used to construct boundaries of neutral subsonic hinge-moment stability, with respect to the parameter $C_{h\delta}$, as shown by figure 3. Combinations of supersonic hinge-moment ratio and vent location represented by the regions to the left of the boundaries would be expected to result in overbalanced, or positive, values of $C_{h\delta}$.

The regions to the right of the boundaries represent the underbalanced condition. The dashed curves on the figure show the supersonic hinge-moment ratios that would be expected when the vents are located at various fractions of the flap chord from the hinge line. For the $0.5c_f$ location the ratios

range from 0.25 for the 30-percent-chord flap to 0.37 for the 15-percent-chord flap. Smaller supersonic hinge-moment ratios could, of course, be obtained by locating the vents farther to the rear, although the construction of the flap probably would then be more difficult. The optimum vent location probably cannot be specified with any reasonable degree of accuracy, because of the approximations of the present analysis and because of uncertainty as to the kind of control-force characteristics that might be desired in an airplane. The indications are, however, that when the vents are located approximately midway between the flap hinge line and the wing trailing edge, satisfactory balance performance may be obtained at both subsonic and supersonic speeds.

Since the geometry of the balance is completely defined by the supersonic hinge-moment ratio (see equation (3)), certain practical design considerations can easily be investigated. One important consideration concerns the maximum flap deflection that can be obtained when the overhang length required for satisfactory aerodynamic characteristics is used. The term "maximum flap deflection," as used herein, refers to the angular motion of the flap that corresponds to a movement of the nose of the balance plate from the wing mean thickness position to the inner surface of the wing skin. The total available angular motion, including both positive and negative flap deflections, is twice the value of $\delta_{\max}$ given in the following analysis. The flap could, of course, be so designed as to permit larger deflections in one direction than in the other, although such arrangements have not been considered herein.

In making estimates of the maximum flap deflection, it has been assumed that the nose of the flap could be deflected to within 0.005c of the external surface of the airfoil; in addition, a balance span equal to the flap span and a flap chord equal to 20 percent of the wing chord have been assumed. Results on certain pertinent aspects of the geometry of the simple attached type of balance are presented in figure 4. In order to reduce the supersonic flap hinge moments to approximately 25 percent of the values that would be expected with an unbalanced flap, an overhang chord of about 85 percent of the flap chord would be required. For this overhang, maximum flap deflections of about $\pm 9^\circ$ could be obtained with an NACA 65A008 airfoil and of about $\pm 12^\circ$ could be obtained with an NACA 65A010 airfoil. These deflections probably are smaller than could be tolerated in an actual design. Another difficulty is that the long overhang requires that the cantilever-type cover plates be unsupported for a considerable fraction of the wing chord. In these respects a geared overhang appears to have certain practical advantages over the attached overhang which has just been discussed.

One possible arrangement of a geared overhang balance used with an aileron is illustrated in figure 5. For the arrangement shown, a wing spar could be located between the balance and the flap. The spar would have to be slotted to allow passage of air from the vents to the balance chamber.

The balance plate could be hinged just forward of the spar and geared back to the flap by any suitable linkage. Such an arrangement would allow good support for the balance-chamber cover plates as well as for the flap and should permit the use of a much greater overhang length than would be practical with the simple attached overhang arrangement.

With the geared overhang, any desired maximum flap deflection can be obtained through proper selection of the linkage ratio $\frac{\delta\delta_b}{\delta\delta_f}$. The results of calculations of the required overhang and linkage ratios for predetermined values of the supersonic hinge-moment ratio and of the maximum deflection are presented in figure 6. If it can be assumed that space permits installation of a balance having a chord of from 100 to about 120 percent of the flap chord, then the geared overhang appears to provide a considerable advantage over the attached overhang. With $\frac{c_b}{c_f} = 1.20$, a supersonic hinge-moment ratio as low as 0.25 can be obtained with maximum flap deflections of $\pm 15^\circ$ for the NACA 65A008 airfoil or $\pm 20^\circ$ for the NACA 65A010 airfoil. For a given overhang length an increase in the maximum deflection decreases the effect of the balance on the hinge-moment parameters.

GENERAL DISCUSSION

From purely theoretical considerations, the principle of the sealed internal balance seems suitable for application to control surfaces required to operate under subsonic and fully developed supersonic flow conditions. The manner in which the balance would perform at transonic speeds can only be speculated on in the absence of actual test results. Location of the balance-chamber vents to the rear of the control-surface hinge line would, however, be expected to cause the balancing moment to be roughly proportional to the hinge moment of the plain flap, since the balancing pressures would be determined by the load carried by the flap. Satisfactory operation may possibly be obtained therefore, in spite of the wide variations in chordwise load distribution that may occur at transonic speeds. A control surface equipped with a sealed internal balance vented at locations rearward of the hinge line might also be expected to resist buffetting, since the required ducts and vents should provide some natural damping.

Certain practical difficulties of the proposed arrangement are apparent. The necessity of providing at least three airtight flexible seals would indeed complicate the construction and maintenance of the balances. All but the seal at the nose of the balance plate might possibly be eliminated, however, through the use of flexible tubular ducts from the vents to the

balance chamber. A second difficulty is that the relatively large space required by the balance may not always be available. With the geared overhang arrangement, however, the balance could be located between wing spars and, therefore, cause little conflict with the required structure. In general, it appears that the difficulties might well be overcome provided the advantages indicated by the present analysis are substantiated by experiments.

CONCLUDING REMARKS

Results of a simplified analysis indicate that a device that utilizes the principle of the sealed internal balance may possibly function satisfactorily at subsonic flight speeds below the speed at which local sonic velocities occur and in fully developed supersonic flow. By locating the balance-chamber vents about midway between the control-surface hinge line and the wing trailing edge, a high degree of balance probably could be obtained in both types of flow. Such a balance also appears to have certain points in its favor for operation at transonic speeds.

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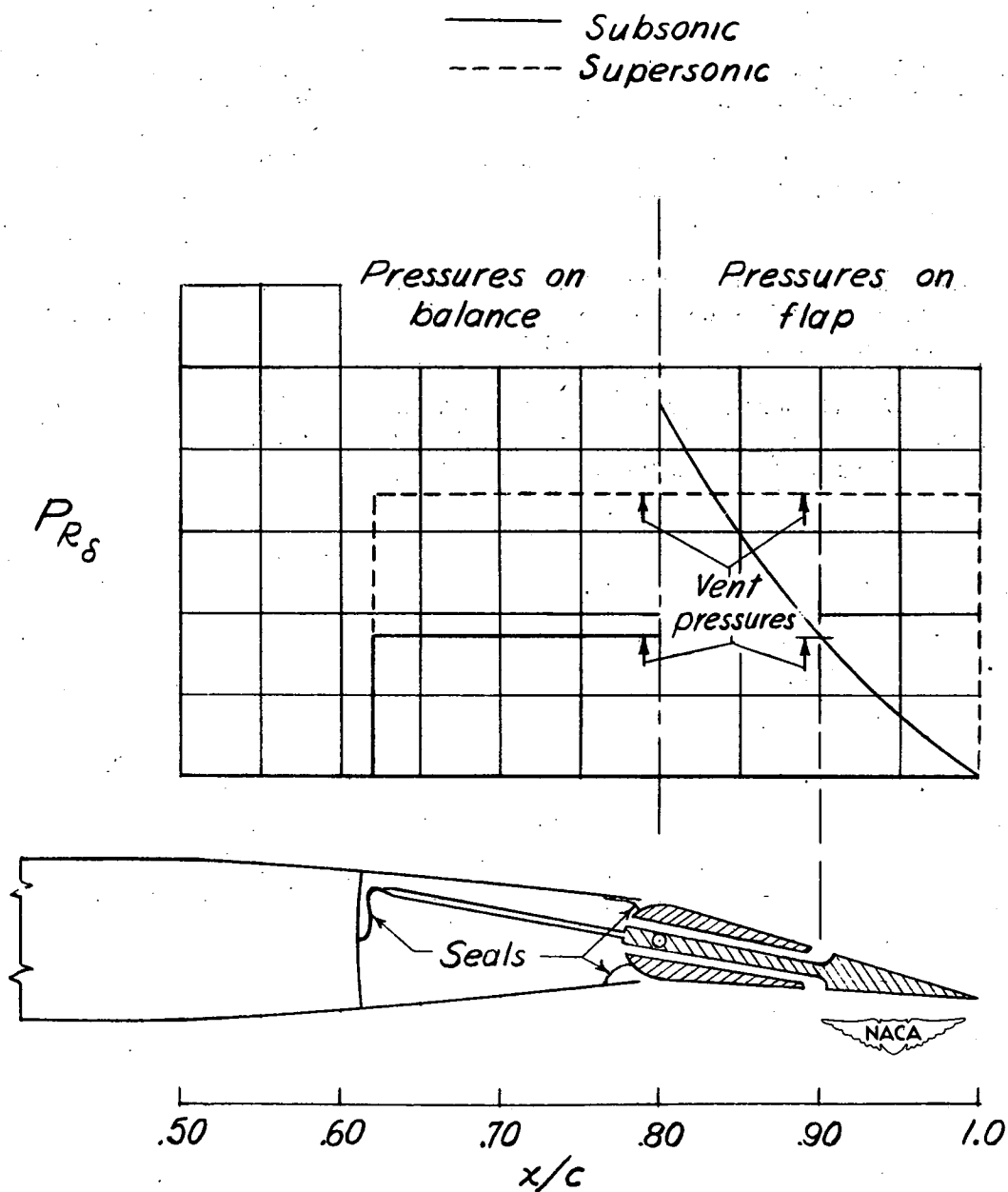
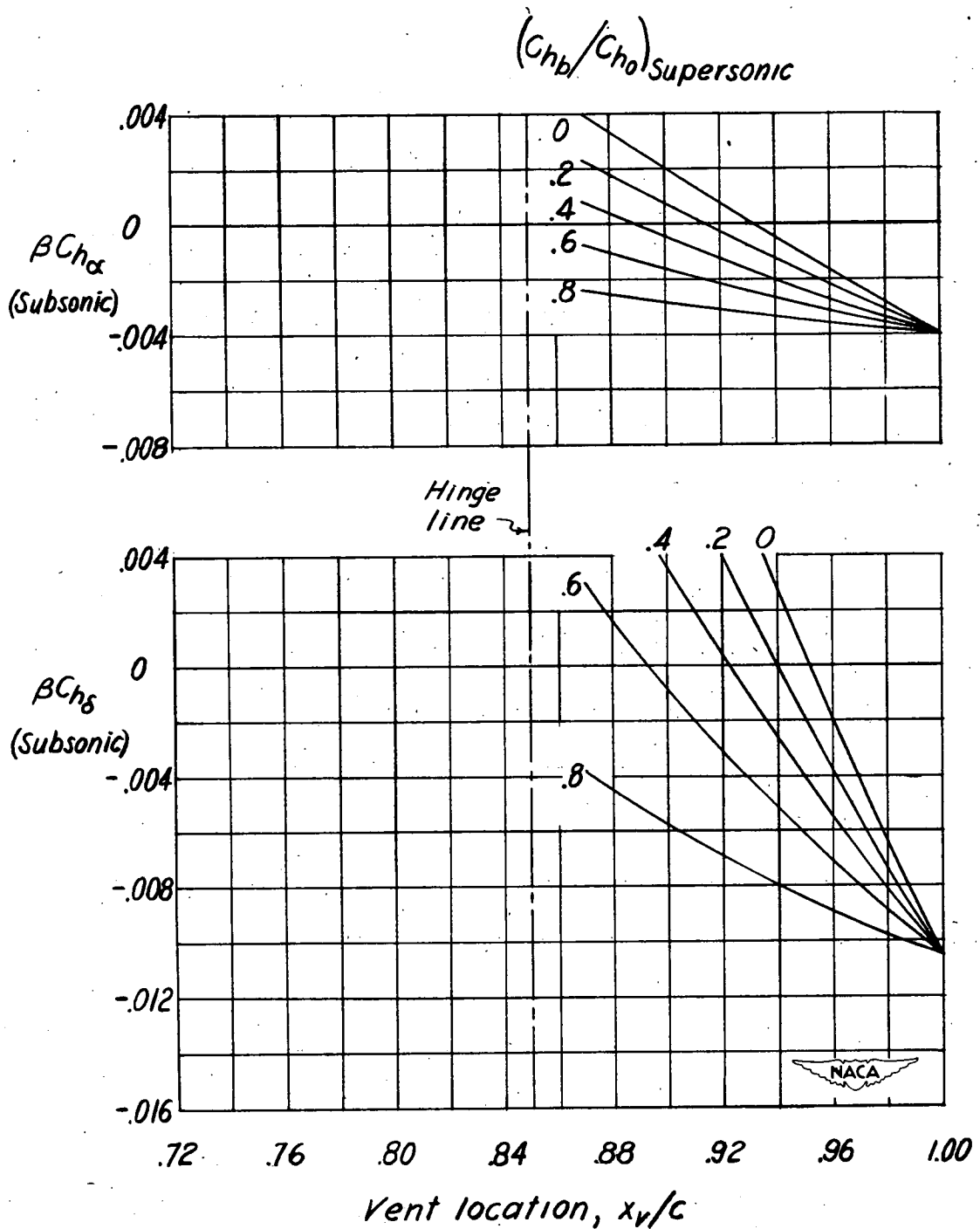
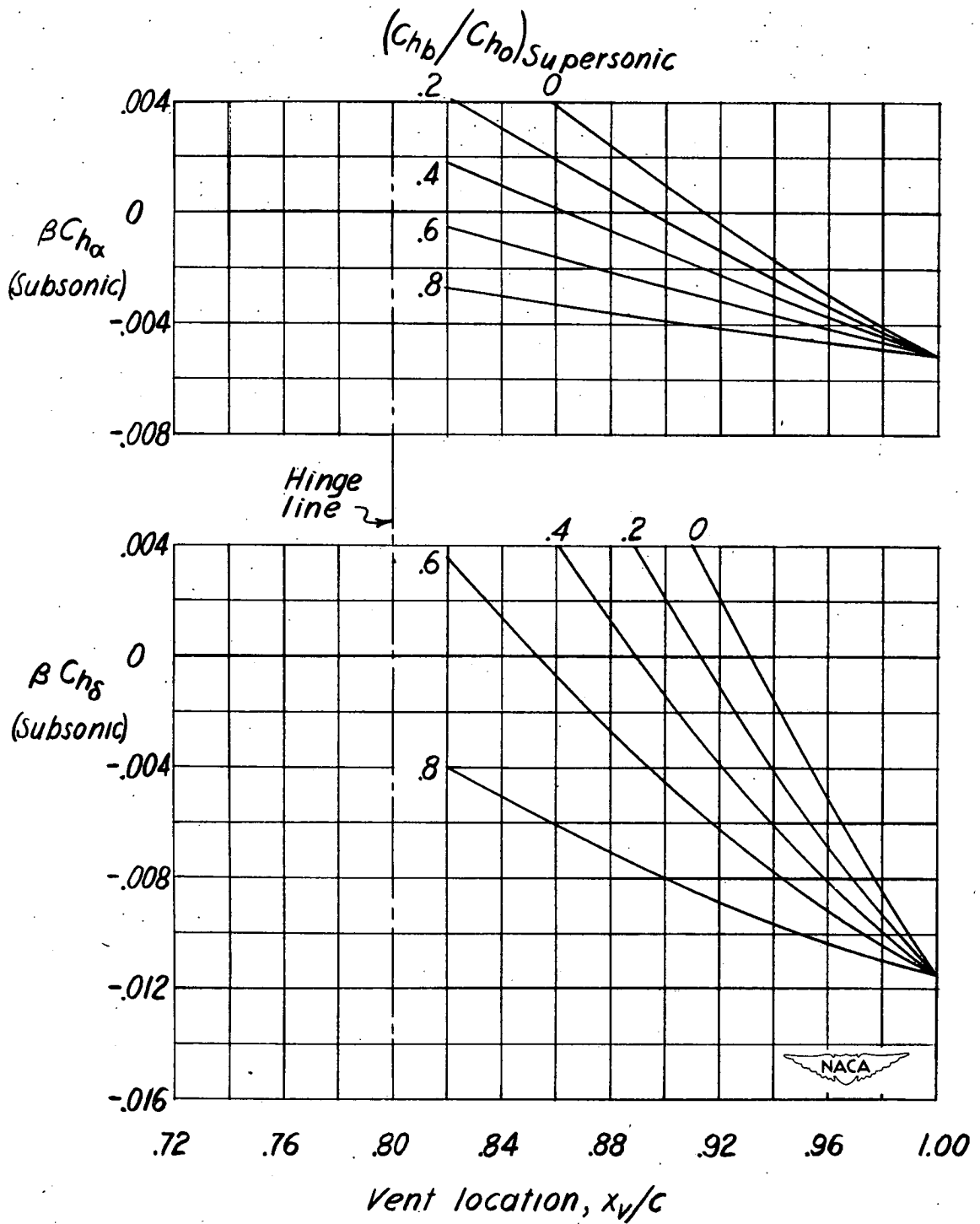


Figure 1.- Diagram illustrating the application of the sealed internal balance for subsonic and supersonic conditions.



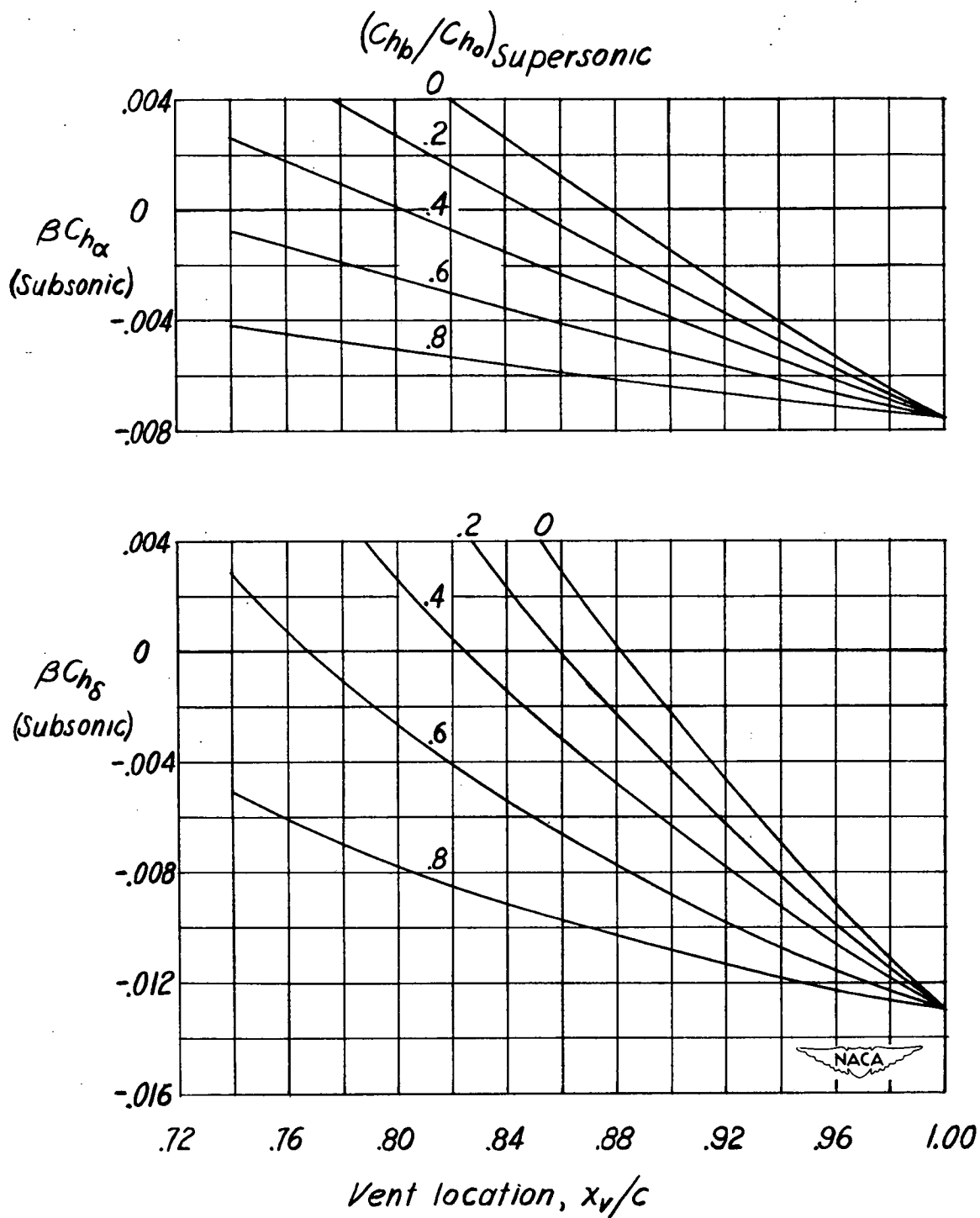
(a) $c_f/c = 0.15$.

Figure 2.- Relation of the subsonic hinge-moment parameters to the vent location and to the supersonic hinge-moment ratio.



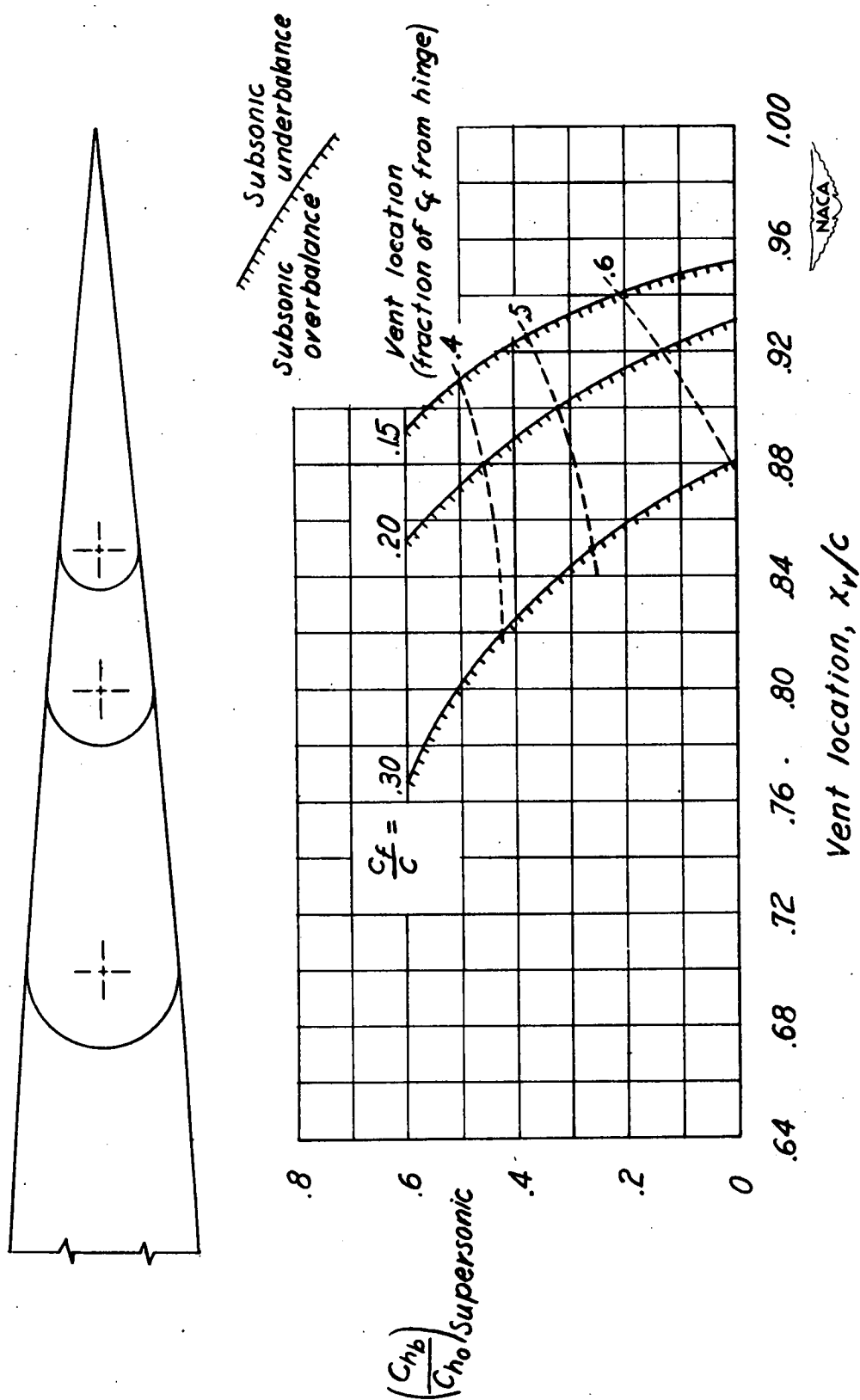
(b) $c_f/c = 0.20$.

Figure 2.- Continued.



(c) $c_f/c = 0.30$.

Figure 2.- Concluded.



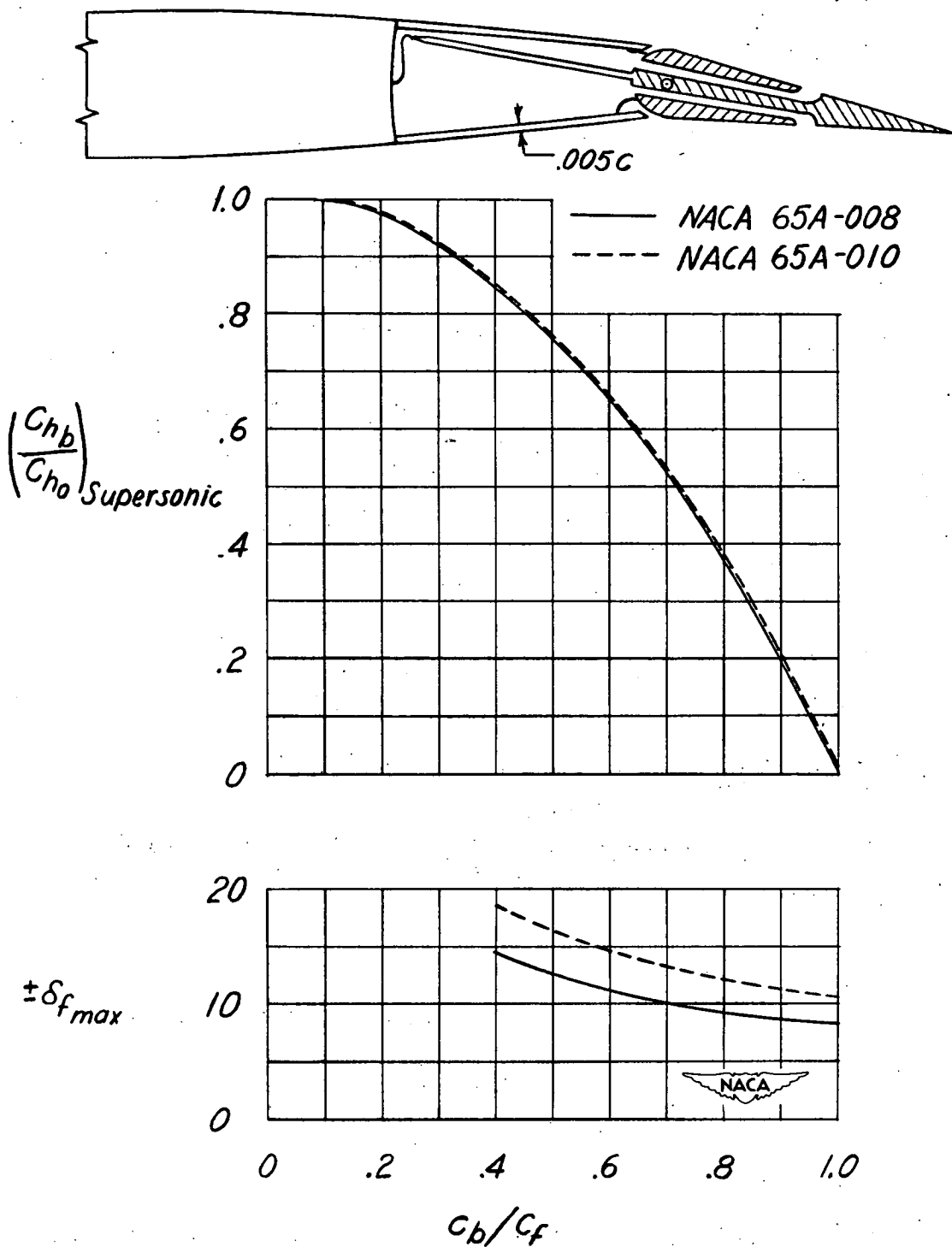


Figure 4.- Relation of the maximum deflection and the balance chord ratio to the supersonic hinge-moment ratio for a flap with an attached balance. $c_f = 0.20c$; $b_b = b_f$.

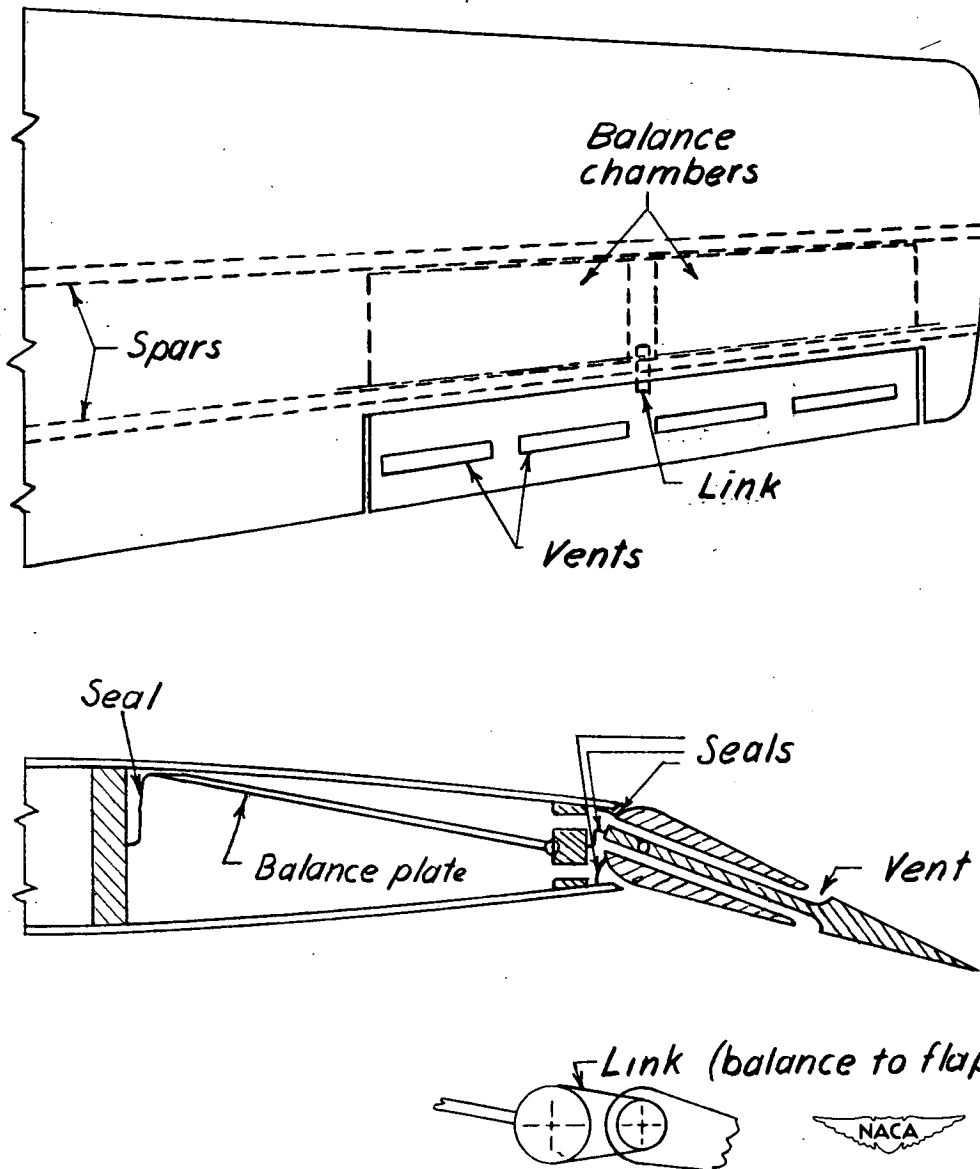
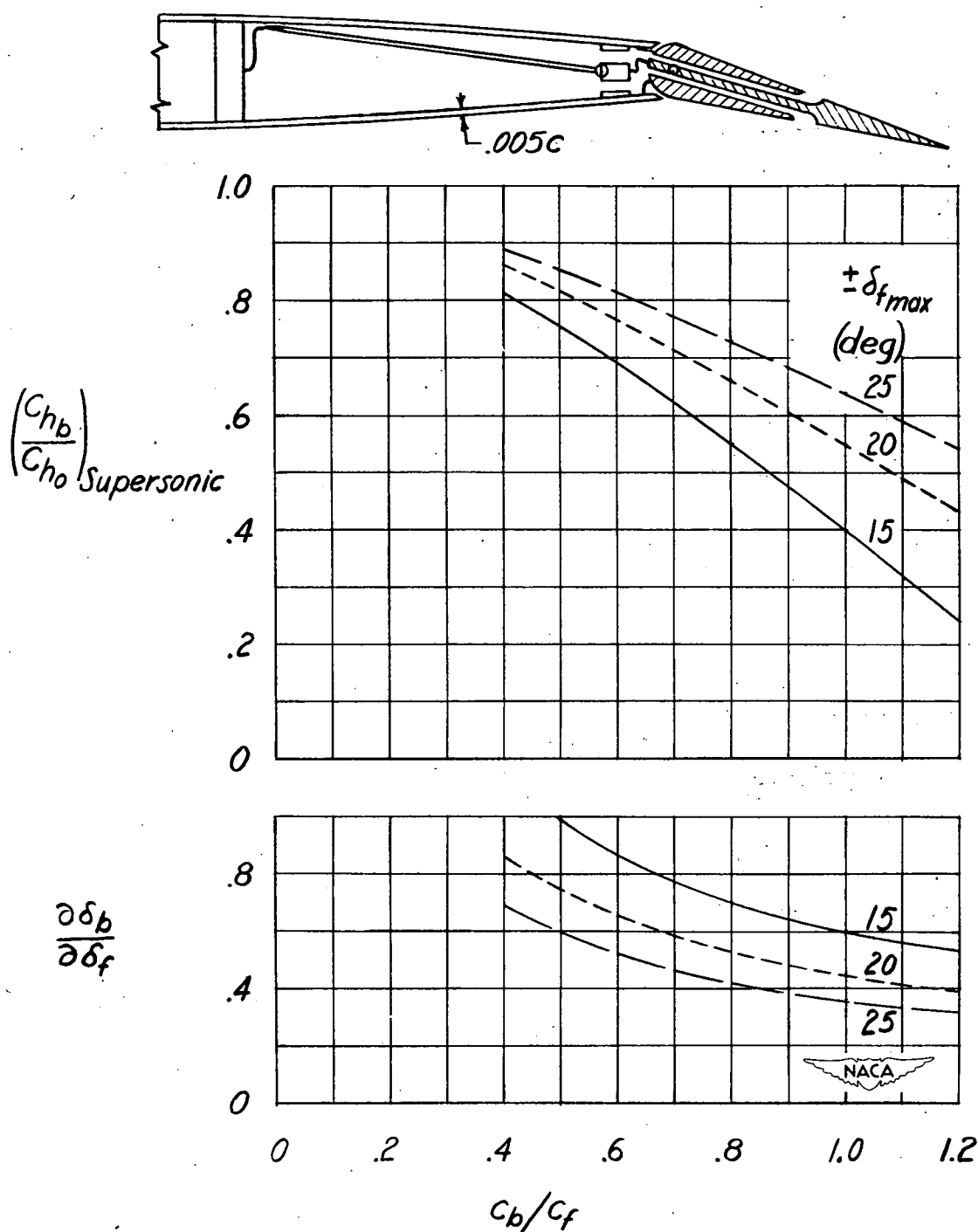
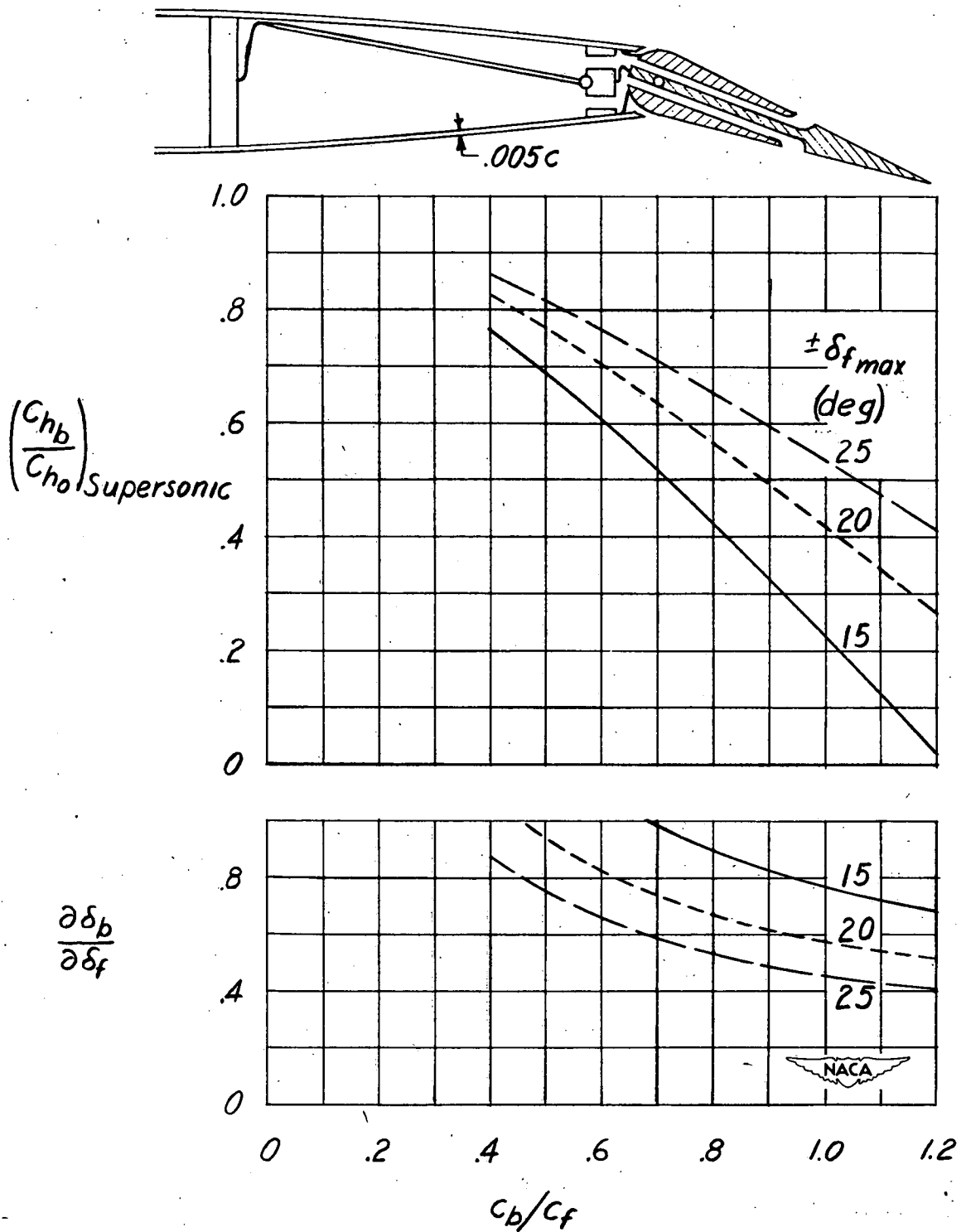


Figure 5.- Possible arrangement of a geared balance used with an aileron.



(a) NACA 65A-008 airfoil.

Figure 6.- Relation of maximum deflection, balance chord ratio, and balance linkage ratio to the supersonic hinge-moment ratio for a flap with a geared balance. $c_f = 0.20c$; $b_b = b_f$.



(b) NACA 65A-010 airfoil.

Figure 6.- Concluded.